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Title: Safety Calculations for the Flight of Primary and Secondary Fragments

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Safety Calculations for the Flight of Primary and Secondary Fragments

HE Safety Day

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Los Alamos National Laboratory

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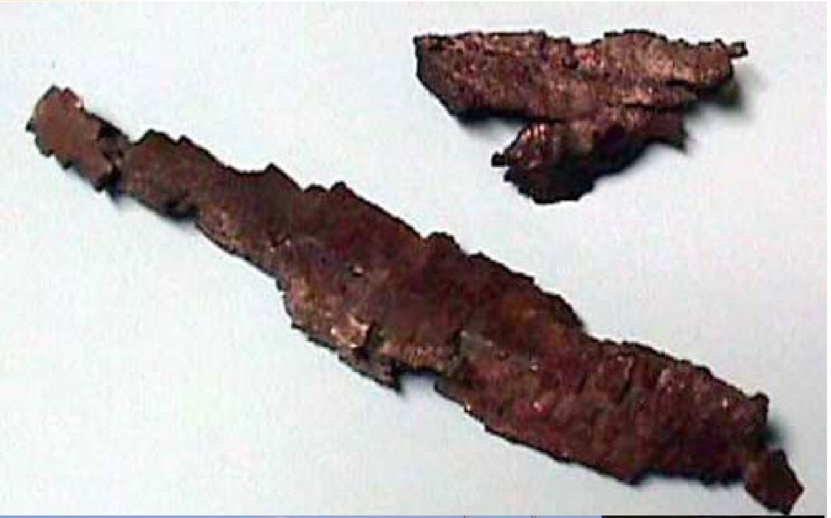
WX-6 (retired)

ABSTRACT – Knowing the maximum ranges of explosive-driven fragments is critical to a safe and efficient testing operation. This presentation explores the aerodynamics of fragments with sometimes counterintuitive conclusions. The "Davis Range," traditionally used at Los Alamos to set clearance distances for fragment-producing HE-driven experiments, is developed in detail, exploring the assumptions and safety factors that are built in. Also developed (in a cursory manner) is a new methodology for estimating the maximum range of secondary fragments (those launched by the HE blast wave).

Explosive-driven fragments (shrapnel) are a principal long-range operational hazard

- Rough-edged
- Strips or Chunks
- Metal or Minerals



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Explosive-driven fragments (shrapnel) are a principal long-range operational hazard

- Initial velocities up to 3000 m/s
- Typical ranges up to 100s of meters

Its not the running into things: its the running into people we want to avoid

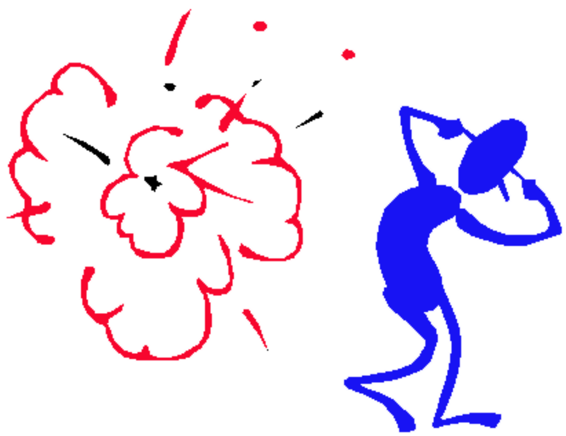
- The military has collected fragment and blast data on munitions for decades
  - The results are codified in DoD 6055.9 “DOD Ammunition and Explosive Safety Standards”
- DOE adopted these rules as requirements
  - Hazardous fragments
    - 15-79 J: serious injury
    - >79 J: severe injury or death
- DOE ESM allows reduced hazard zones if there is appropriate analysis

There are two classes of fragments: Primary & Secondary

- Primary fragments come from metal directly or nearly in contact with the explosive
  - Pressures are considerably above the yield strength of the material
  - Generally torn from the expanding case, 1-3 km/s launch
  - Can be whole plates (often by design)
    - Planar shock or initiation experiments
    - Active armor plates
- Secondary fragments are usually launched by the close-in blast from the explosive
  - Pressures below the yield strength of the material
  - Structures likely remain whole, 10s-100s m/s launch
  - Can “fly” like a Frisbee® (if you’re unfortunate)

Predicting the formation and flight of shrapnel is important for safe and *efficient* operations

- Explosives move material in predictable ways
  - The size of metal fragments can be estimated
  - Initial velocity and direction (of primary fragments) can be estimated
  - The trajectory (flight path) can be estimated
    - Aerodynamics applies to chunks as well as aircraft



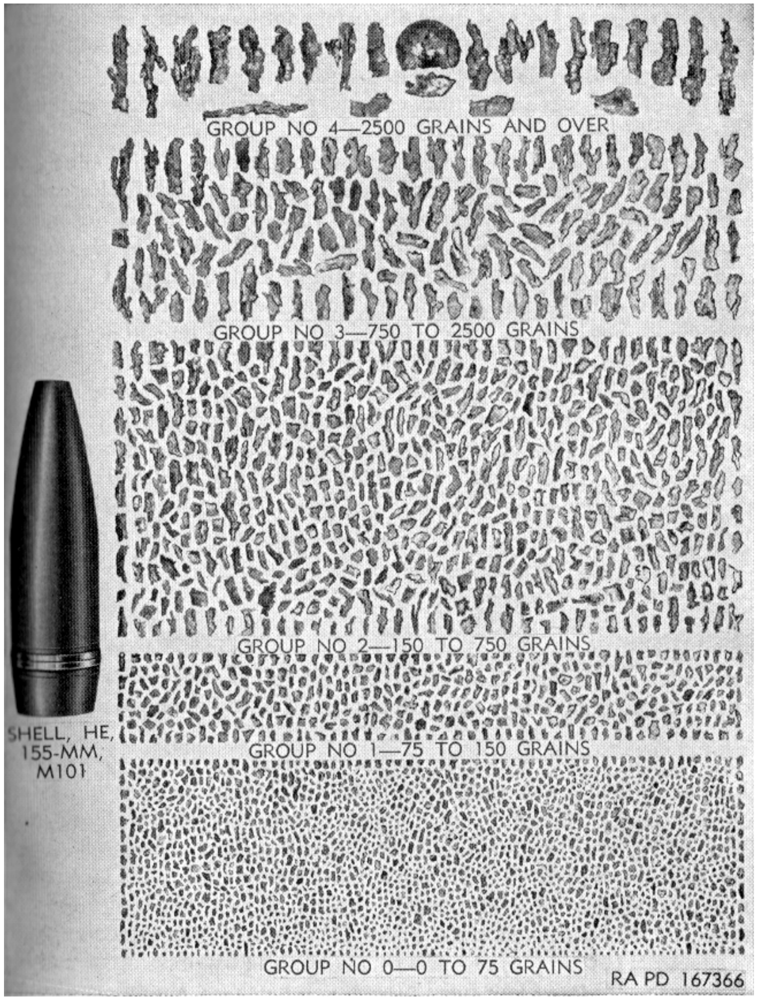
- Hazard zones are usually defined by the “largest” primary fragment
  - “Largest” can mean weight, or specific dimension
- Secondary fragments must be identified for each test configuration
  - There is a new method to estimate launch velocity and range

The fundamental parameters for every trajectory are what you might expect

- The fragment
  - Mass
  - Geometry
    - Drag
    - (Lift)
- The launch
  - Initial velocity
  - Initial angle
- The air
  - density
- The flight
  - Drag orientation
    - “Normal”
    - Tumbling
    - Aerodynamically unfortunate
  - Lift orientation
    - “Normal” & Tumbling
    - Angle-of-Attack

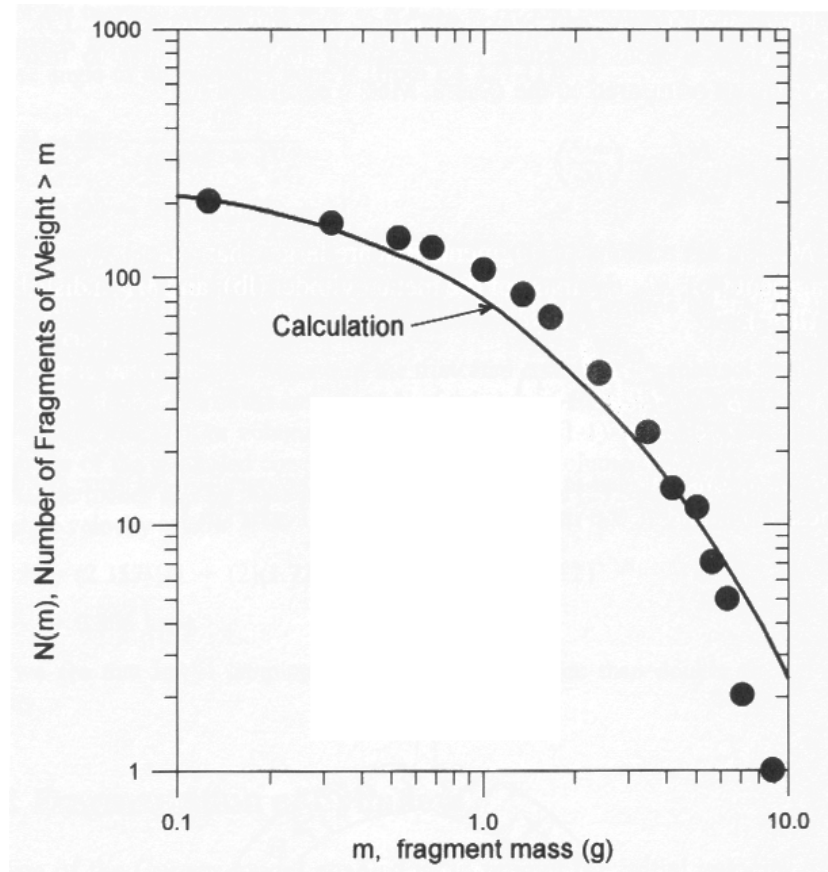
Knowing the mass and geometry of the fragments is the starting point

- Explosives generally break things
  - The sizes of the pieces are important for knowing:
    - How far the fragments fly
    - What damage (hazard) they present
  - Grooves and scoring of encasing metal can alter the size distribution of fragments
    - Keeping fragment size large enough to be effective is by design



Mott’s distribution for fragment size (weight) is a useful approximation to measured values

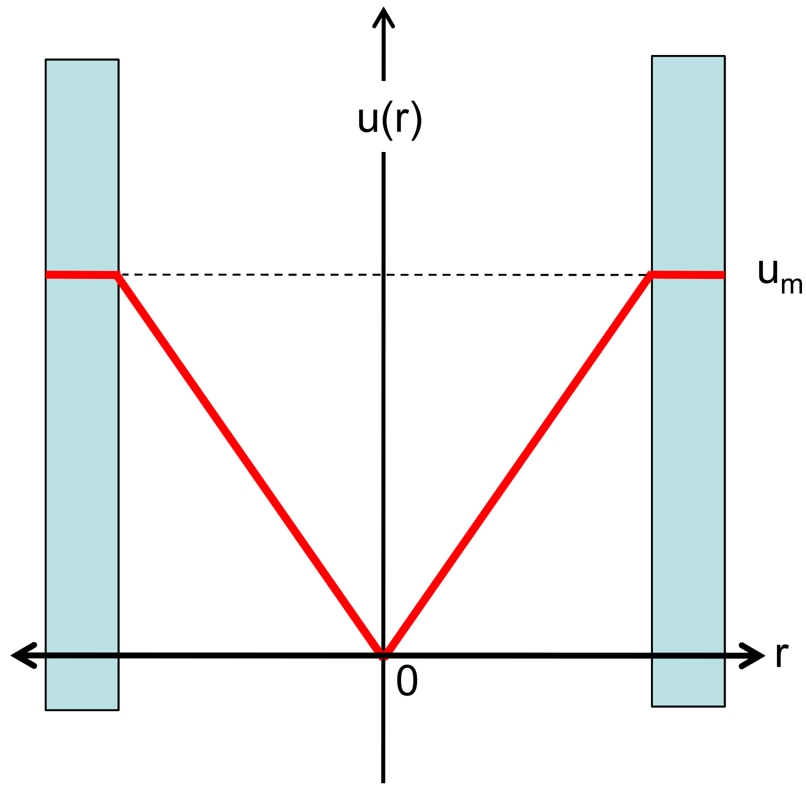
- The Mott theory tends to overestimate the largest fragments
  - The biggest fragments are the fewest
  - The biggest fragments fly the farthest
- The parameters in the distribution are functions of the metal/explosive pair
  - Only the most common pairs have been calibrated
- Other theoretical or heuristic distributions are also available



Initial velocities of most primary fragments are simply estimated by a Gurney analysis

- Gurney analysis is algebraic
  - Uses energy and momentum conservation
  - Assumes linear velocity gradient of detonation products
- Closed-form formulae for initial velocity of primary fragments (e.g., cylinder)

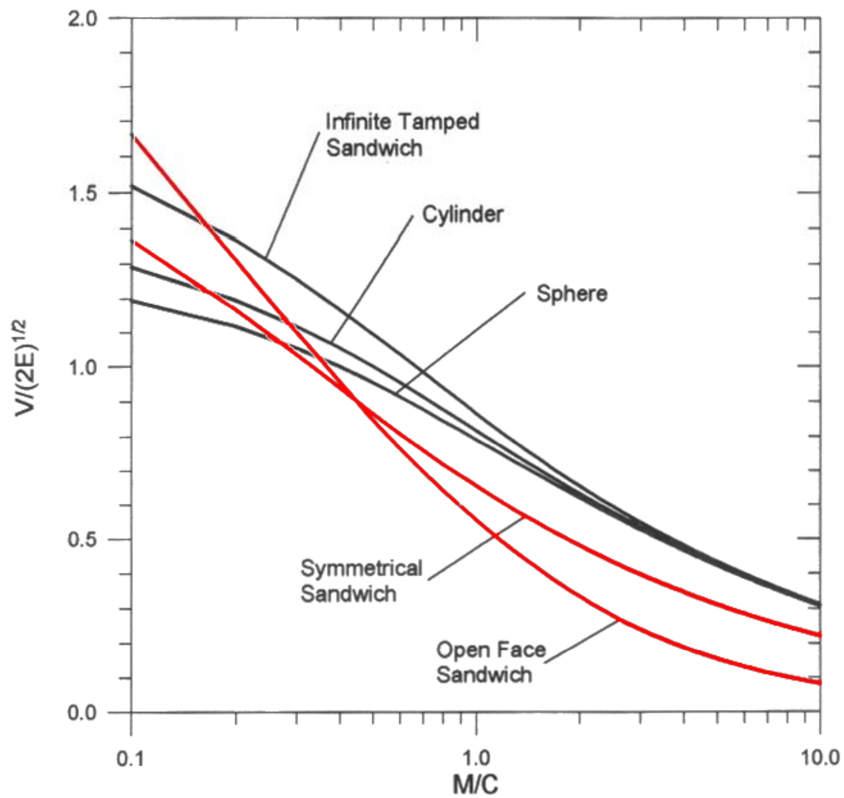
$$v_{launch} = \frac{\sqrt{2E}}{\sqrt{\frac{M}{C} + \frac{1}{2}}}$$



C = total mass of HE
M = total mass of metal
u_m = velocity of metal = v_{launch}

Gurney analysis provides analytical estimates for primary fragment initial velocities

- The infinite tamped sandwich, cylinder, and sphere analyses are a family of results
  - These are essentially the same problem in 1-, 2-, or 3-D
- The open-face and symmetrical sandwich are also a similar family
  - Both require the explicit use of momentum conservation



Gurney analysis can also be used to estimate the initial launch direction in some configurations

- For a grazing detonation (detonation parallel to the wall)

$$\delta = \frac{\theta}{2} = \sin^{-1}\left(\frac{v}{2D}\right)$$

- Knowing this direction and velocity are first order trajectory parameters
- There is potential for limiting fragment range by thoughtful orientation of the experiment

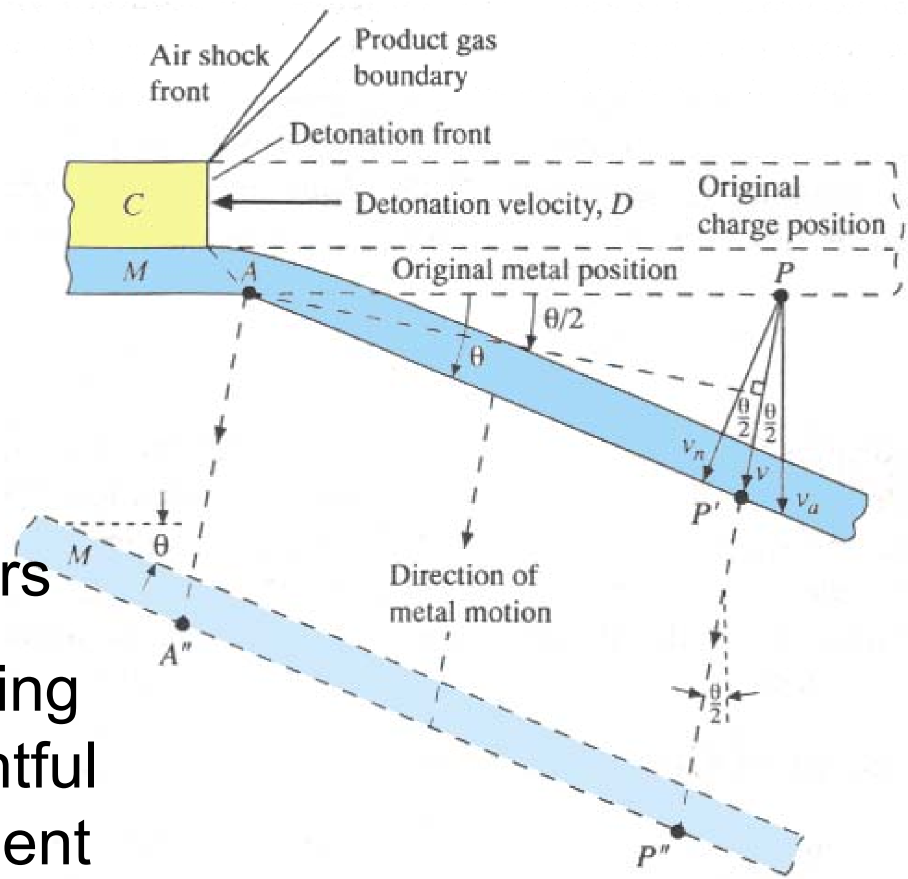
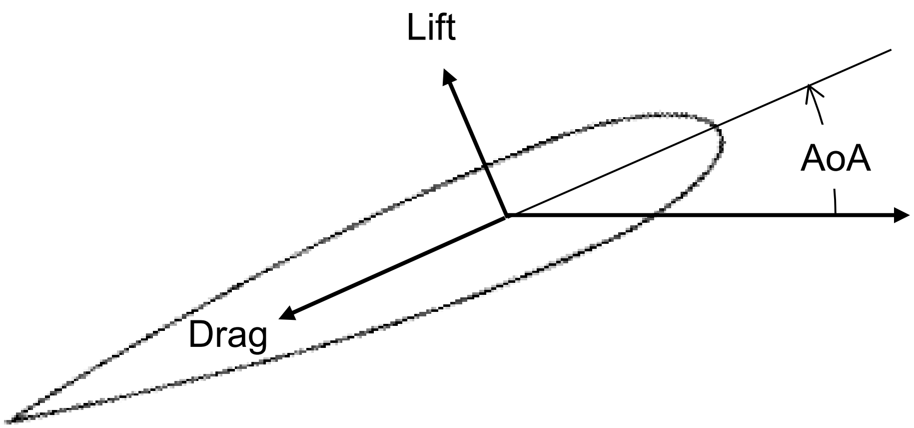
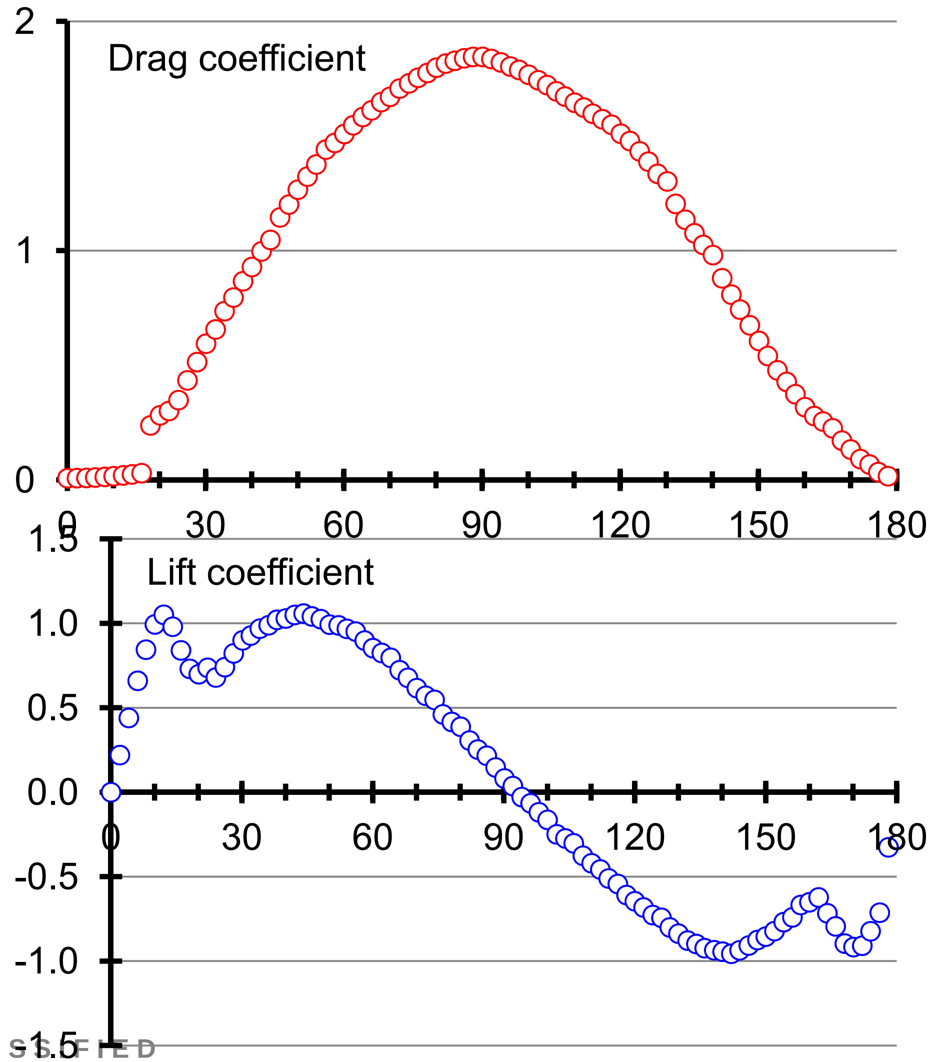


Figure 7.10. Metal projection by grazing detonation.

The flight of any wing (or chunk) depends on the drag and lift

- The aerodynamic coefficients of some model wings were measured by SNLA in 1981
  - Data from the vertical windmill project
  - Measured at all Angles-of-Attack (AoA)





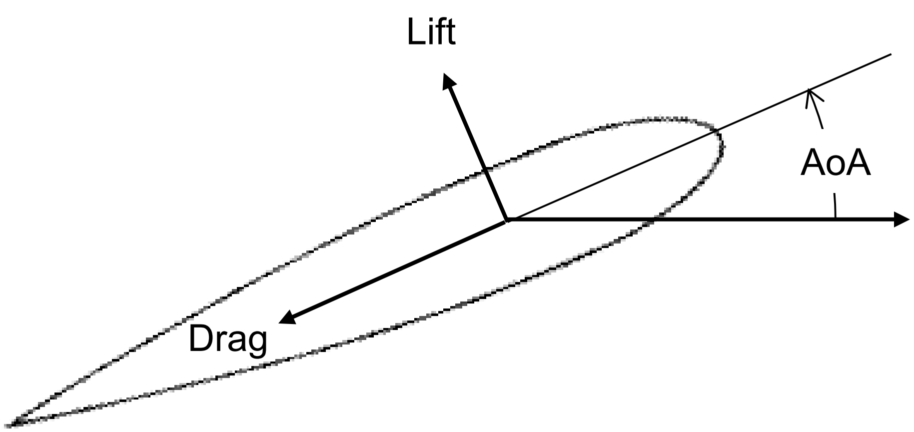
Simple momentum analysis gives crude analytic approximations to these data

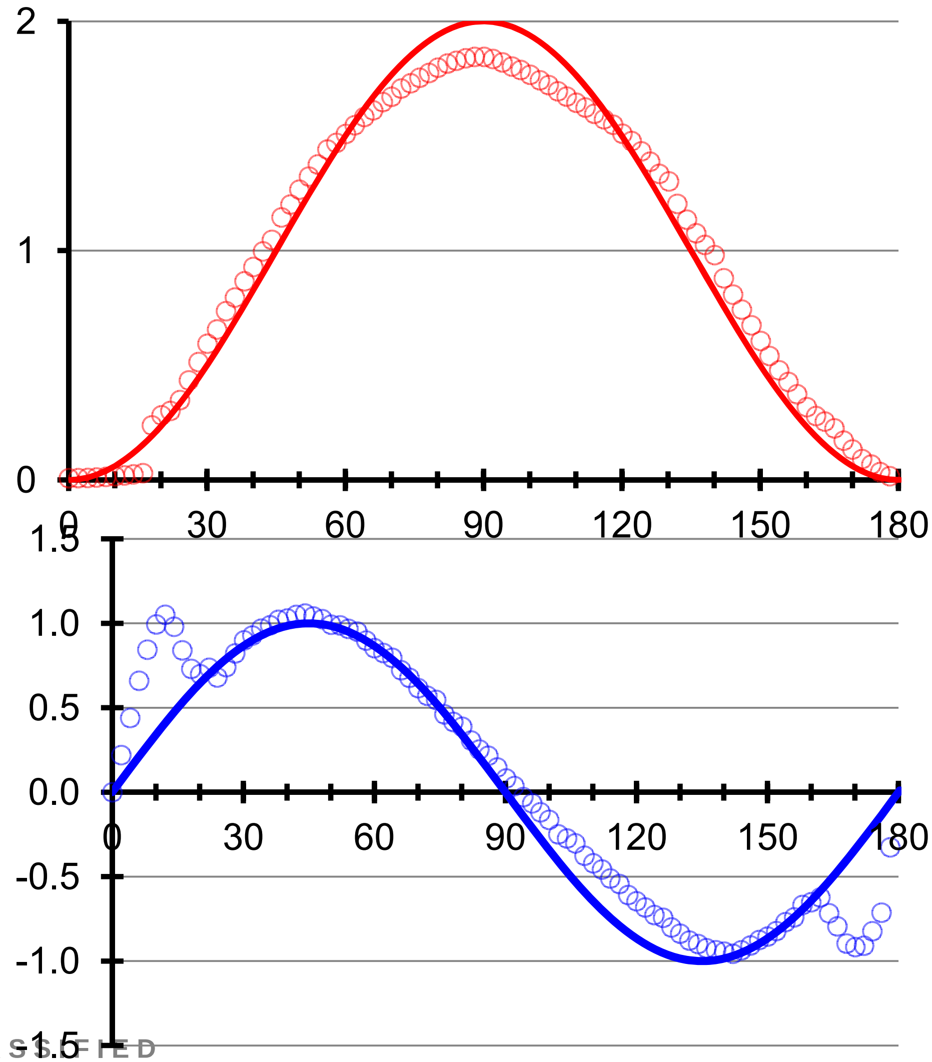
- Drag looks like

  $\sin^2(\mathrm{AoA})$

- Lift looks like

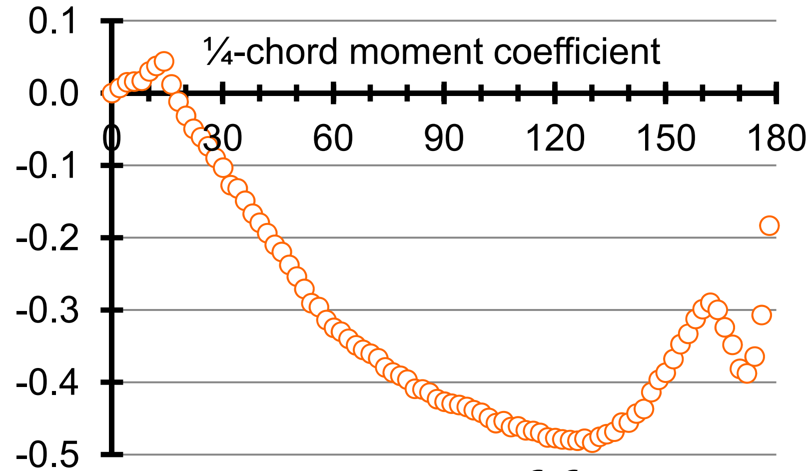
  $\sin(\mathrm{AoA})\cdot\cos(\mathrm{AoA})$



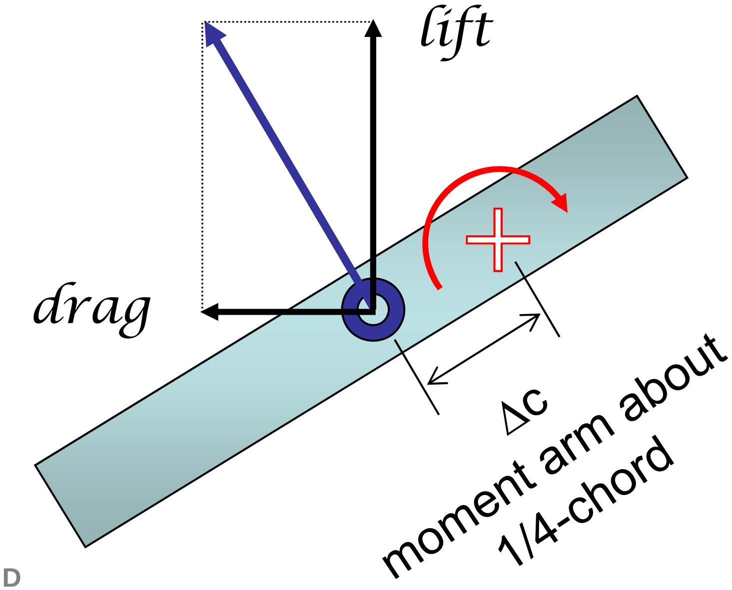


The third aero coefficient is the moment about the 1/4-chord, C_m

- Measures torque around the traditional aerodynamic center
- The distance from the 1/4-chord point to the Center-of-Pressure (CoP) is Δc:



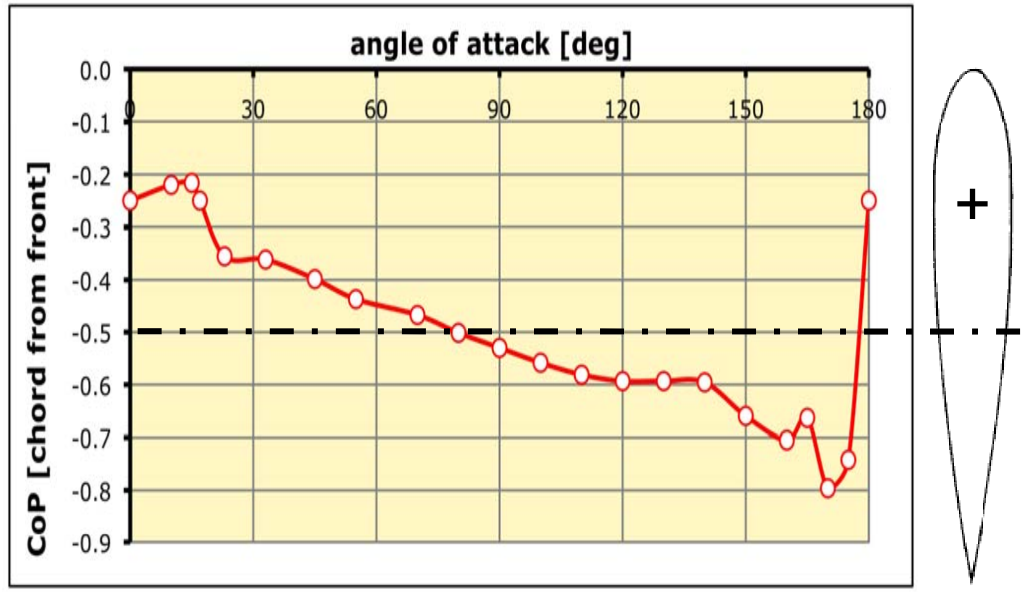
$$C_m = \Delta c \cdot \sqrt{C_l^2 + C_d^2}$$

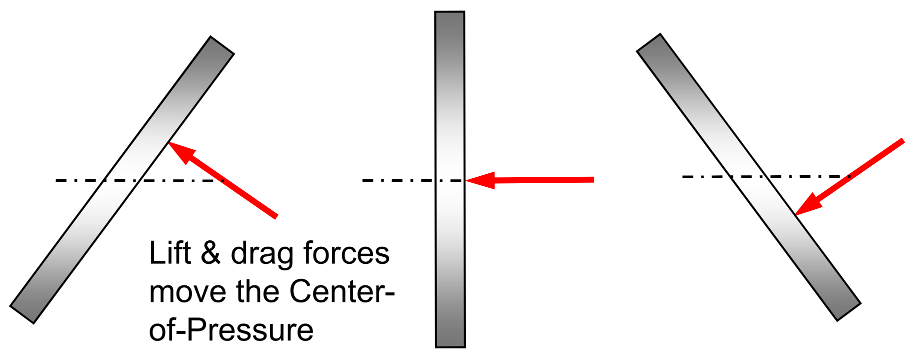


Center-of-Pressure =

Movement of the CoP with AoA provides a restoring force to keep fragments flying with maximum drag

- Deviations from normal flight are self-correcting because lift and drag forces move the center-of-pressure
  - Positive feedback is approximately linear over all Angles-of-Attack
- This notion greatly simplifies trajectory calculations because drag is simple and reasonably constant
  - $C_d \sim 2$
- No net lift
  - $C_l \sim 0$





Full ballistic equations can be cast in terms of areal density or a characteristic length

Motion along trajectory

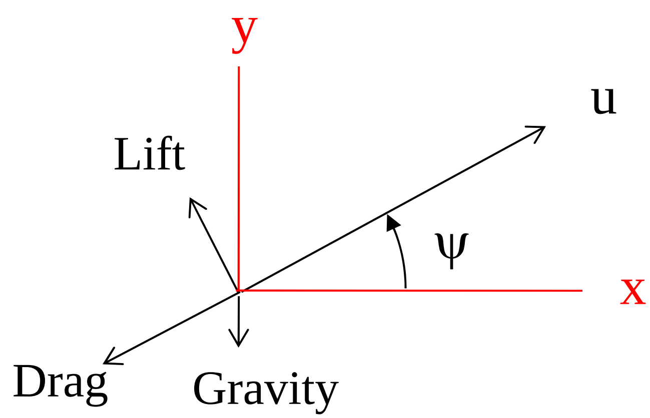
$$\frac{du}{dt} = -g \cdot \sin\Psi - \tfrac{1}{2} C_d \cdot \frac{A}{m} \cdot \rho u^2$$

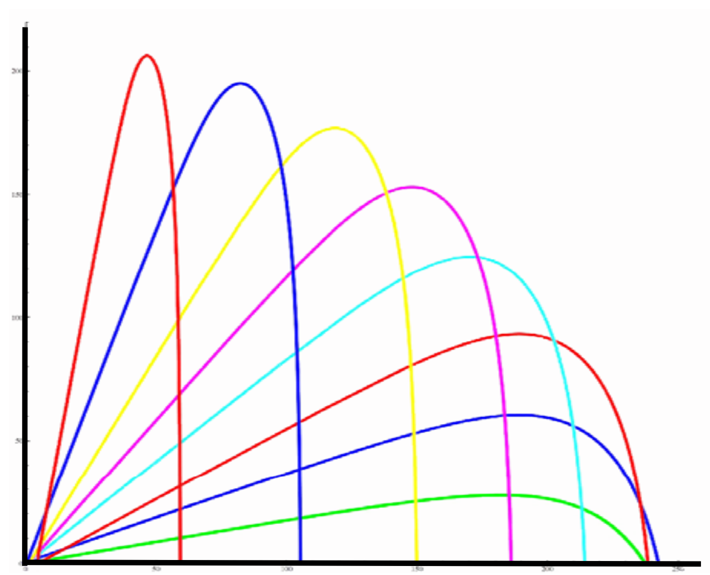
$$= -g \cdot \sin\Psi - \tfrac{1}{2} C_d \cdot \frac{1}{L} \cdot u^2$$

Similar for lift

$$u \frac{d\Psi}{dt} = -g \cdot \cos\Psi - \tfrac{1}{2} C_l \cdot \frac{A}{m} \cdot \rho u^2$$

$$= -g \cdot \cos\Psi + \tfrac{1}{2} C_l \cdot \frac{1}{L} \cdot u^2$$





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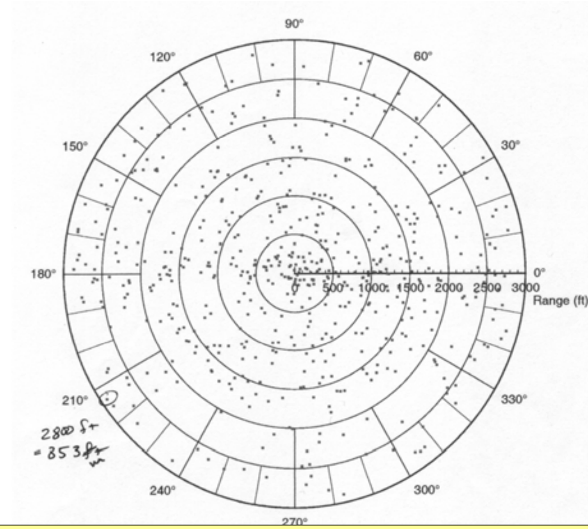
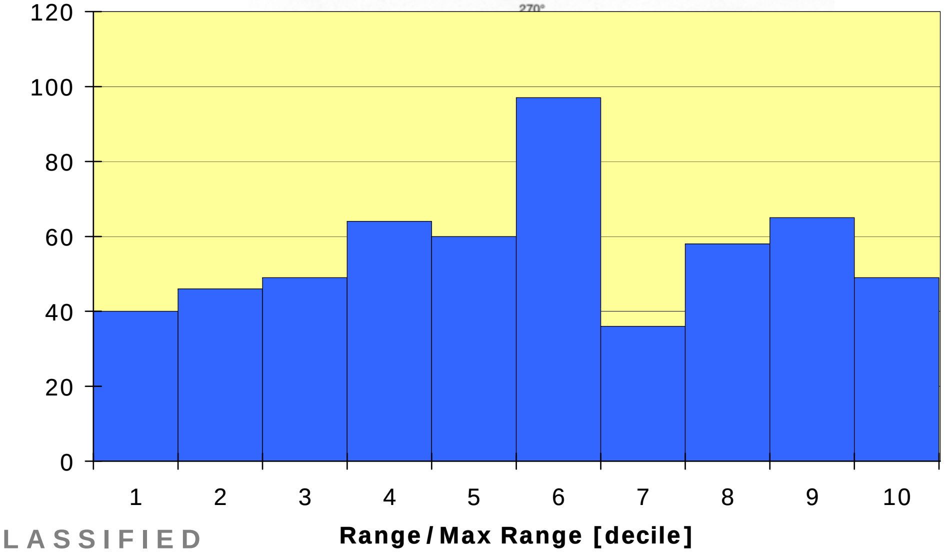
Dave Fradkin (~2000) performed range calculations using straightforward models for size, velocity, & drag

- Measured sizes of DU fragments using x-radiography
  - Fit results to a Mott distribution
- Gurney analysis for initial velocity
- Simple drag model (flat flight)
  - Drag a function of Mach Number
- Random launch angles



- Polar range diagrams are instructive, but not operationally convenient

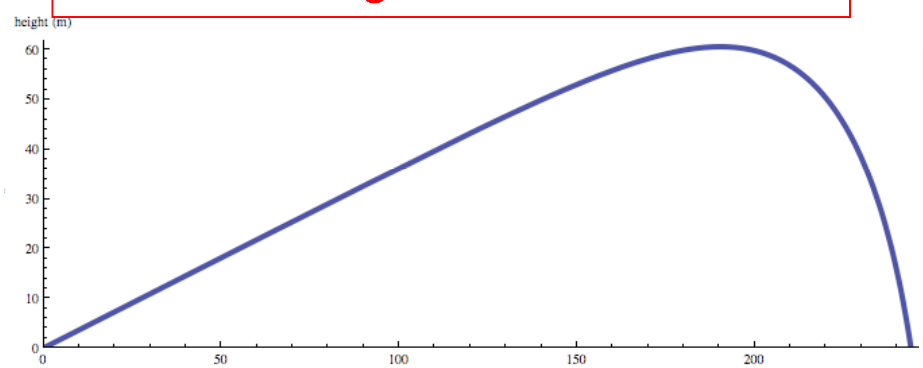


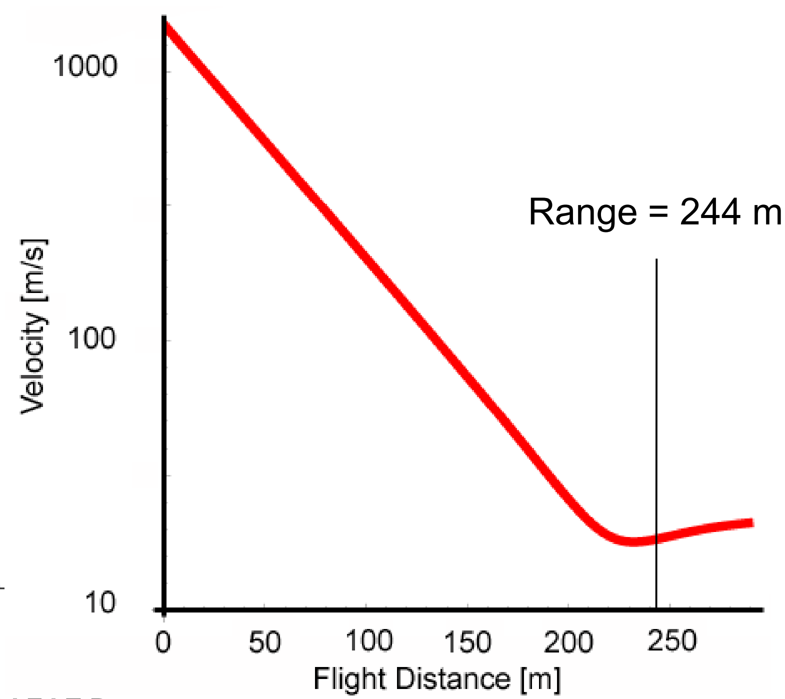
This numerical calculation (with gravity) shows velocity decreases exponentially with distance

- Drag coefficient is constant at 2.0
- Launch angle is for maximum range (later viewgraph)
- Exponential velocity drop over majority of trajectory suggests an approximation:

Gravity is a second-order effect for most of the flight

Aluminum: 1.8-mm thick
L=50 m
U_0 = 1500 m/s
Θ_0 = 20 deg
C_d = 2.0 @ all velocities





Using inertial and drag forces only give a useful solution for velocity as a function of distance

- Air drag is balanced by inertial deceleration

$$\text{deceleration} = \text{drag}$$

$$m \cdot a = (A \cdot h \cdot \rho_m)\frac{du}{dt} = \tfrac{1}{2} C_d \cdot A \cdot \rho_{air} \cdot u^2$$

$$L \cdot \frac{du}{dt} + u^2 = 0$$

Characteristic length

$L = \rho_m * h / ½ C_d * \rho_{air}$

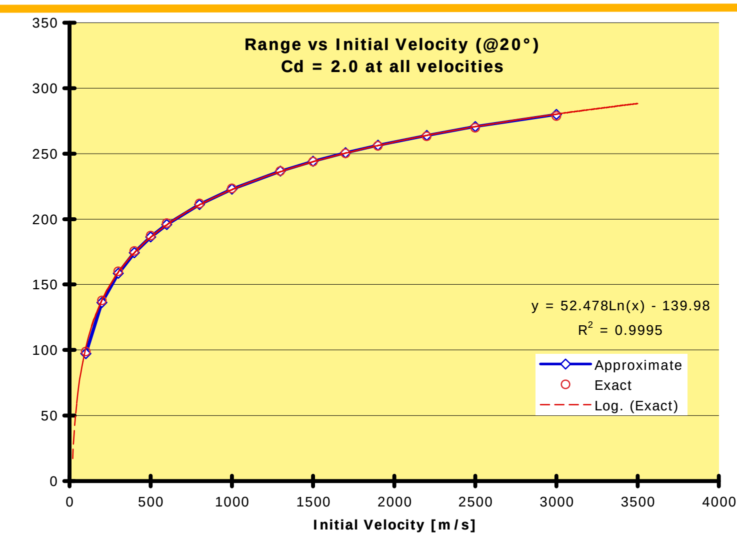
$= (m/A) / ½ C_d * \rho_{air}$

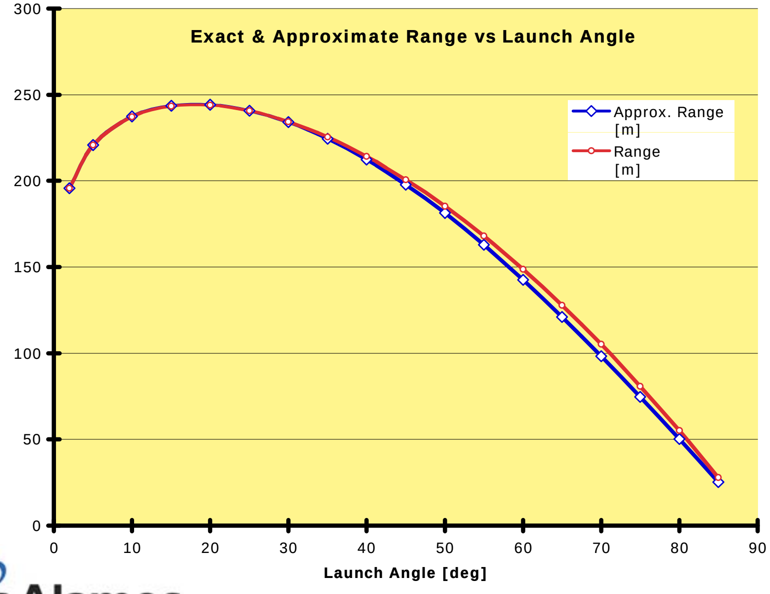
- Solution gives velocity as function of distance and L

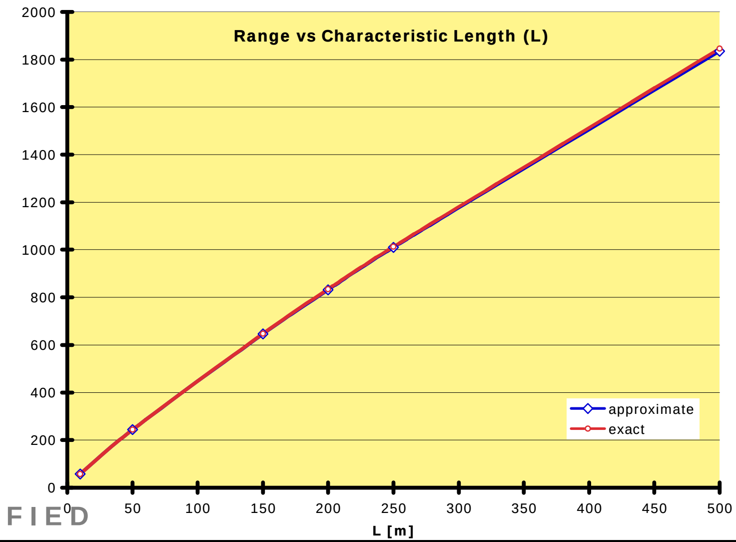
$$\boxed{u = u_0 \cdot e^{-x/L}}$$

The exponential velocity approximation inserted into the full ballistic equations allows an analytical solution:

- These approximate solutions are spreadsheet friendly and agree remarkably well with the full numeric solutions







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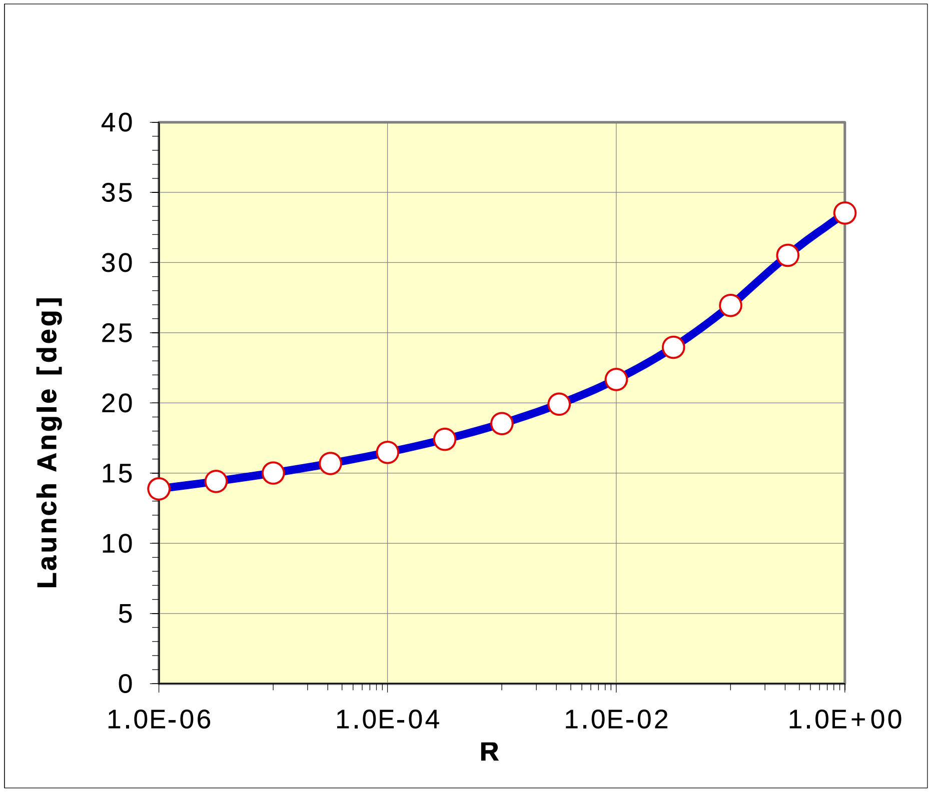
Approximate solution of the ballistic problem with gravity using exponential velocity-distance relation yields an important parameter

- A new parameter of the problem:

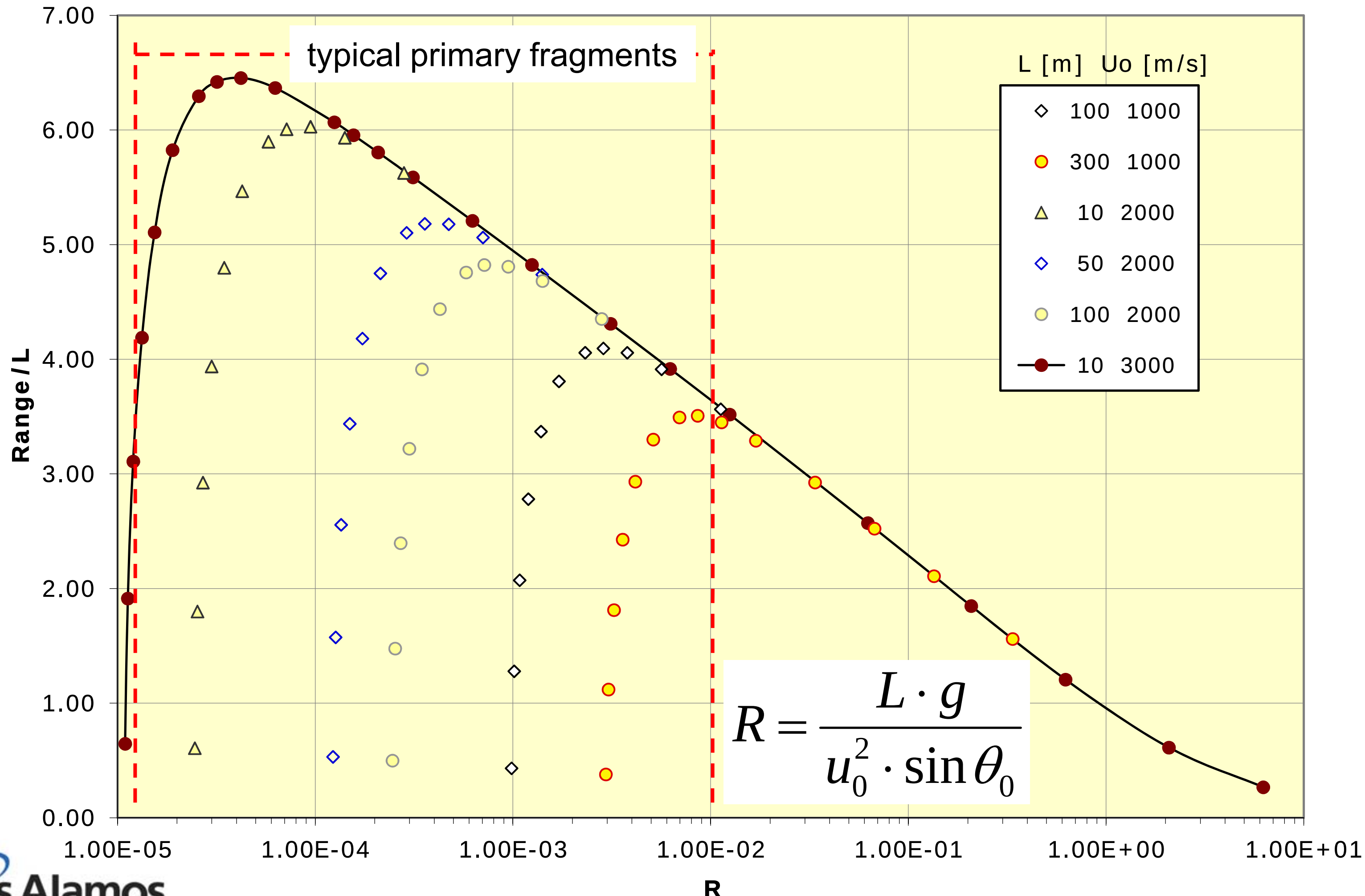
$$R = \frac{L \cdot g}{u_0^2 \cdot \sin\theta_0}$$

  - This has all the things you would expect to affect the flight distance
    - Metal & air density
    - Gravity
    - Initial velocity
    - Launch angle

- Differentiation of the solutions gives Launch Angle for maximum range

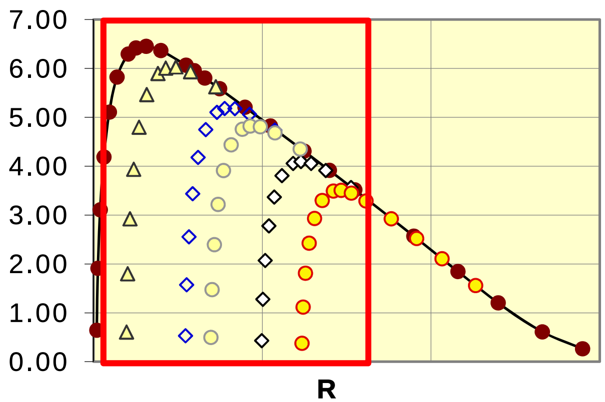


Parameter "R" suggests an envelope for maximum range as a function of Characteristic Length



A further simplification of the maximum-range envelope gives the "Davis" rule:

- Maximum range (X_{max}) only dependent on the Characteristic Length (L)
- Looking at the Range *vs* R plot, all possibilities are contained below ~ 6-7·L



  – We conservatively take "8" as the factor

Max. Range ≤ 8L

X_{max} [m] $\leq 90 \cdot h$ [cm] $\cdot\ \rho_m$ [g/cm^3]

h = length of fragment in direction of flight (thickness)
ρ_m= density of fragment

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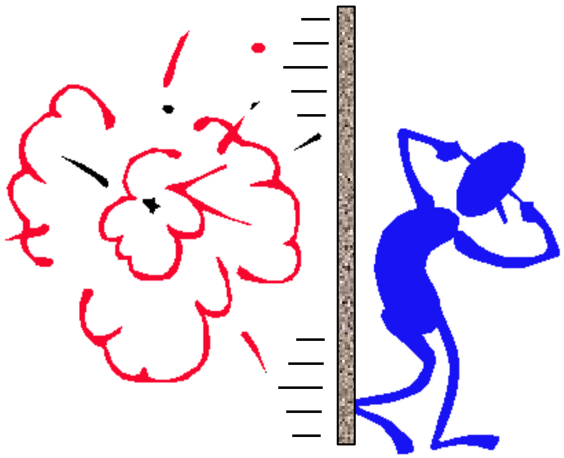
Secondary fragments add additional parameters (complications) to the ballistics

- Launched "whole"
  - Probably short range
- Possibly aerodynamically stable
  - Spin stabilized (Frisbee)
  - Large Characteristic Length, L
    - Length in direction of flight
  - Lift
- 'Difficult to determine' initial velocity
  - Interaction with near-field blast wave
  - Impulsive launch
  - Drag coupling



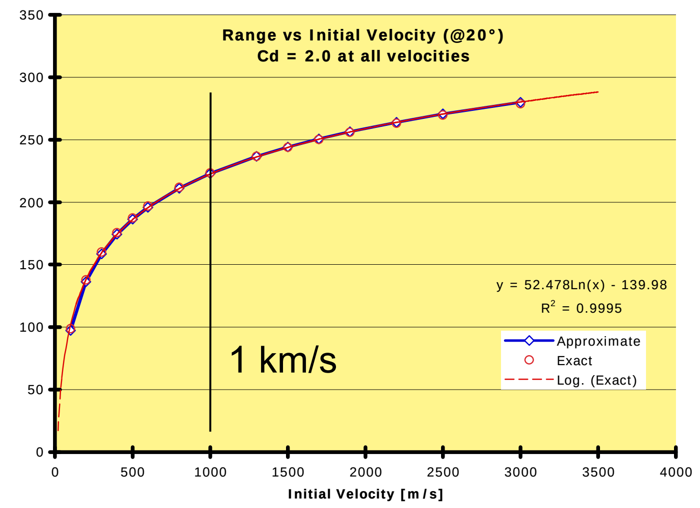
Local experience shows some secondary fragments "fly"

- Now need to know more things
  - Launch velocity, u_0
    - Coupling of close-in blast with object
    - Reflected impulse
    - Drag in blast wave
    - Range is sensitive to u_0

  - Appropriate scaled length
    - Length in the direction of flight may be the "long" dimension
    - Characteristic length (L) can be large
  - Flight with lift and drag
    - Lift & drag coefficients for two or more faced fragments

Local experience shows some secondary fragments "fly"

- Now need to know more things
  - Launch velocity, u_0
    - Coupling of close-in blast with object
    - Reflected impulse
    - Drag in blast wave
    - Range is sensitive to u_0
      - 100s m/s



  - Appropriate scaled length
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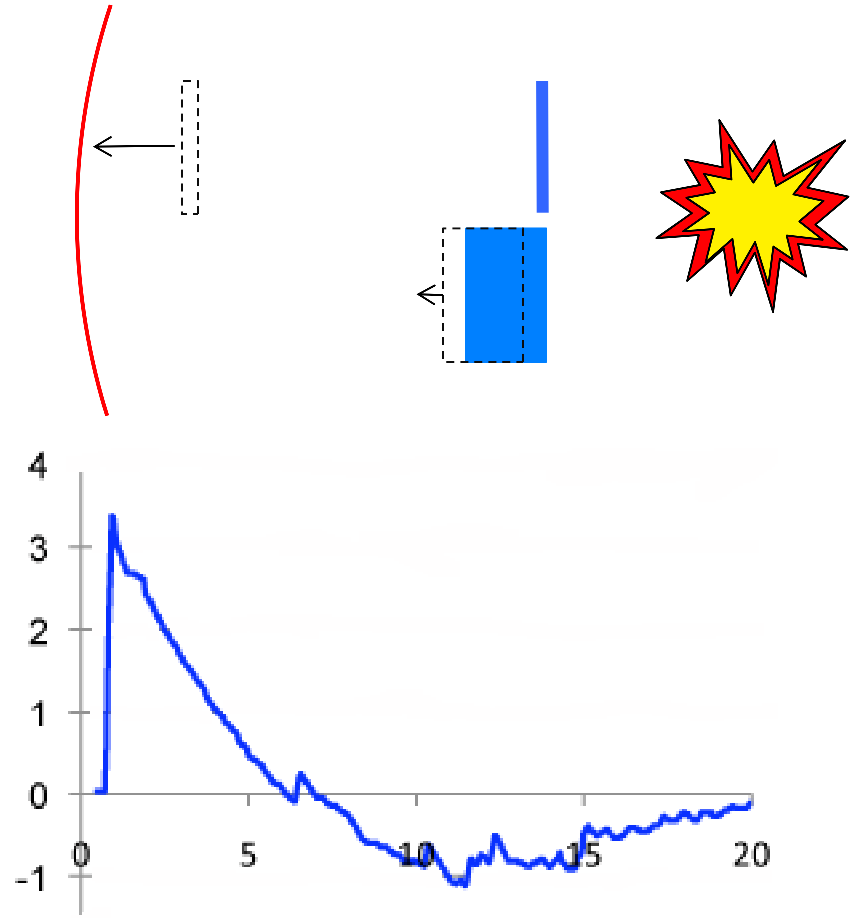
    - Lift & drag coefficients for two or more faced fragments

Sir G. I. Taylor first formulated the idea of a "Fluid-Structure Interaction," (FSI)

- Basic concept
  - Motion of a structure may relieve blast wave pressure acting on it
  - Light weight plates are pushed out of the way by the first part of a blast wave
    - Outrun the later parts of the Taylor wave
    - Full impulse is not delivered
  - Heavy plates hardly move
    - Full reflected impulse delivered
    - Net velocity can be lower



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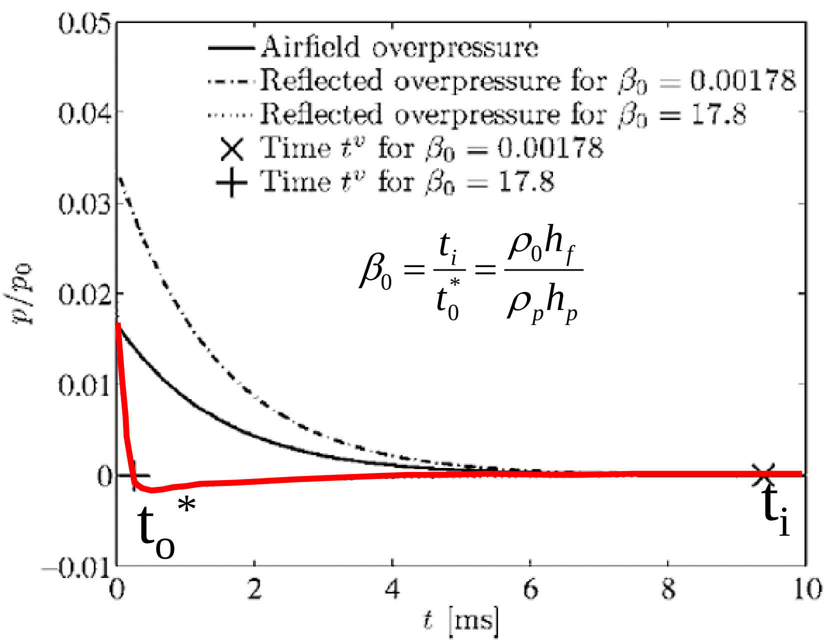
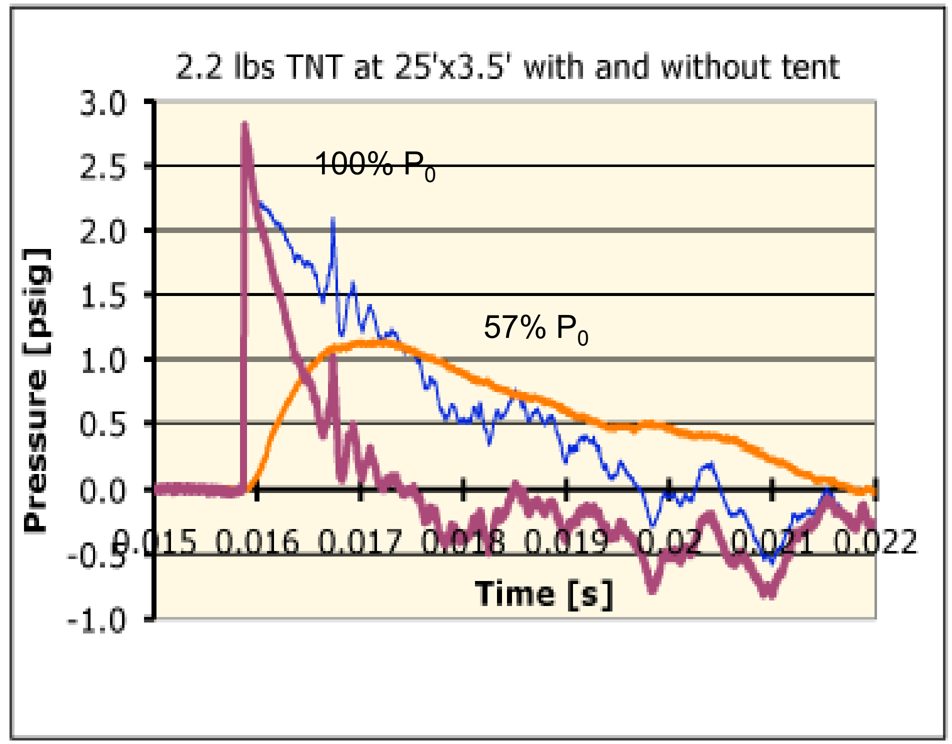
Measurement of blast wave behind tent fabric shows FSI effect

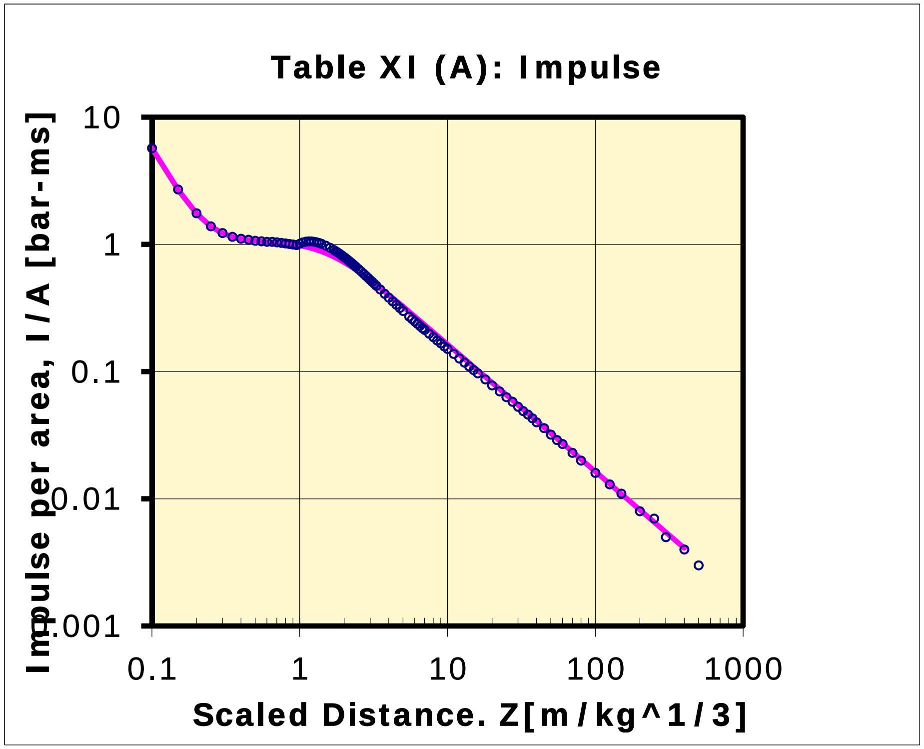
- Tent material areal density = 1.4 kg/m²
- Three-station average: pressure transmission = 57%
- FSI calculated transmission = 54%





The methodology to estimate initial 2°-fragment velocity uses standard blast scaling curves and FSI calculations

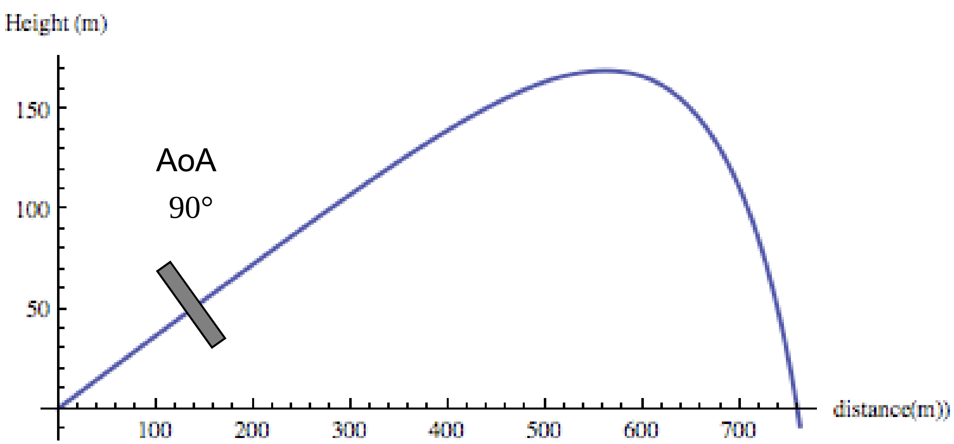
- Equations and methods from Kinney & Graham, "Explosive Shocks in Air, 2nd Ed." estimate the impulse
- Analytical FSI equations from Kambouchev, Noels, & Radovitzky, "Nonlinear compressibility effects in fluid-structure interaction and their implications on the air-blast loading of structures," J. App. Physics **100**, 063519 (2006)
  - K&G: weight & distance of HE ➔ P/P_0, I_{sp}
  - K, N,&R: areal density of 2⊕ ➔ transmitted I_{sp}, u_o(2⊕)
- Entire calculation done on a spreadsheet
  - Result is an initial velocity



Possible flight dynamics of secondary fragments:

- Normal
  - Highest drag orientation
  - No lift, shortest range
- Tumbling
  - Averaged drag coefficient about one-half of maximum (~1)
    - 360° average of aerodynamic-coefficient fits
    - No net lift
  - Low launch velocities (usually)
- Aero-stable
  - Thin edge leading always
  - Possible Angle-of-Attack to trajectory giving lift

Trajectories for four cases: 12”x12”x1” steel
L=203m, u_0=1000 m/s, launch angle=20°, AoA relative to trajectory



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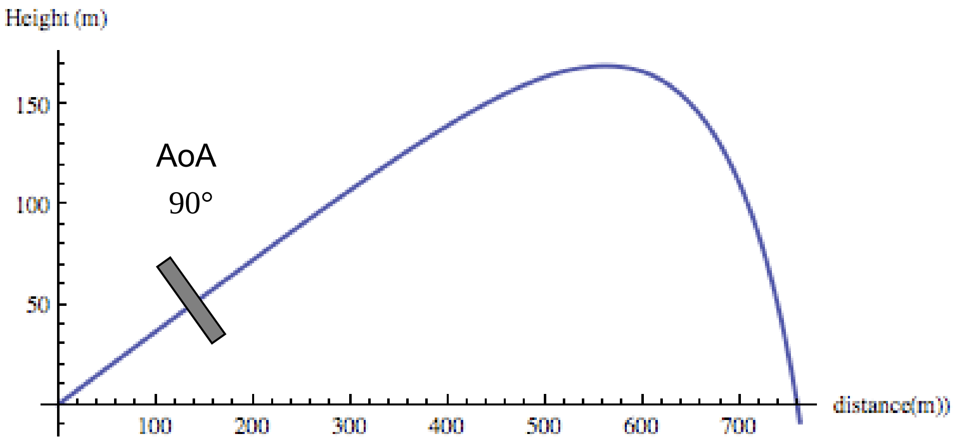

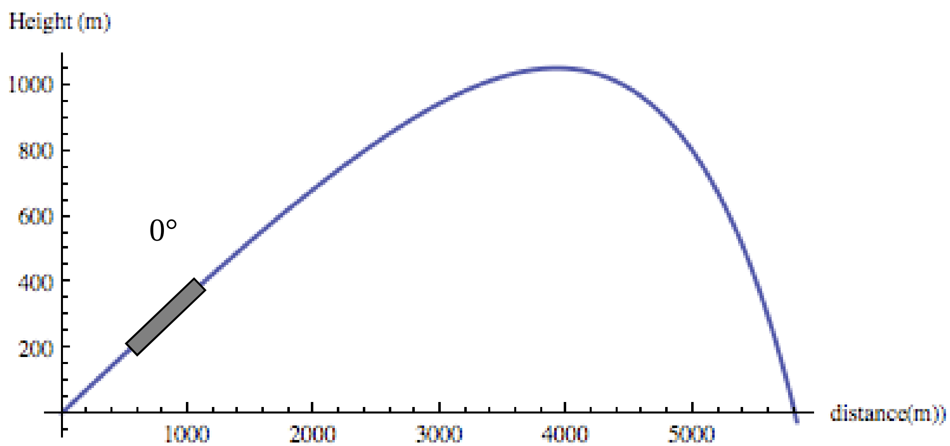

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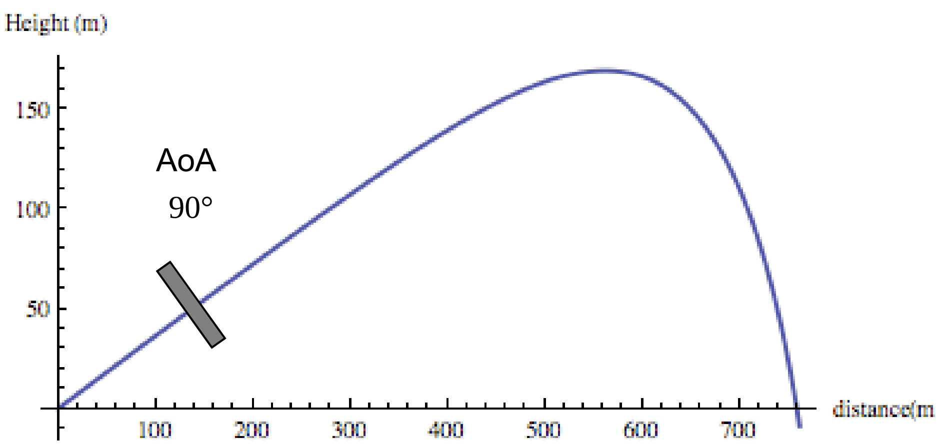

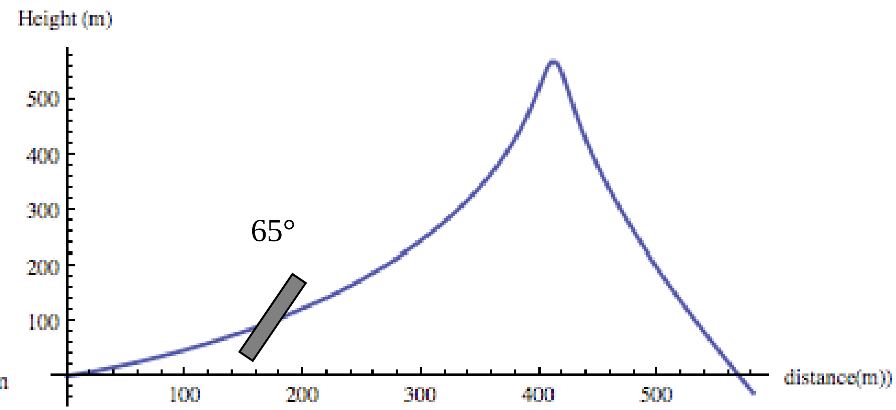

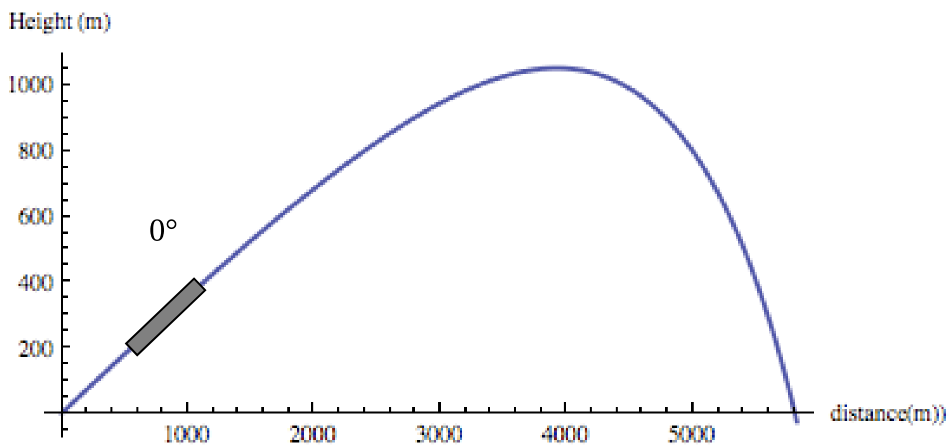

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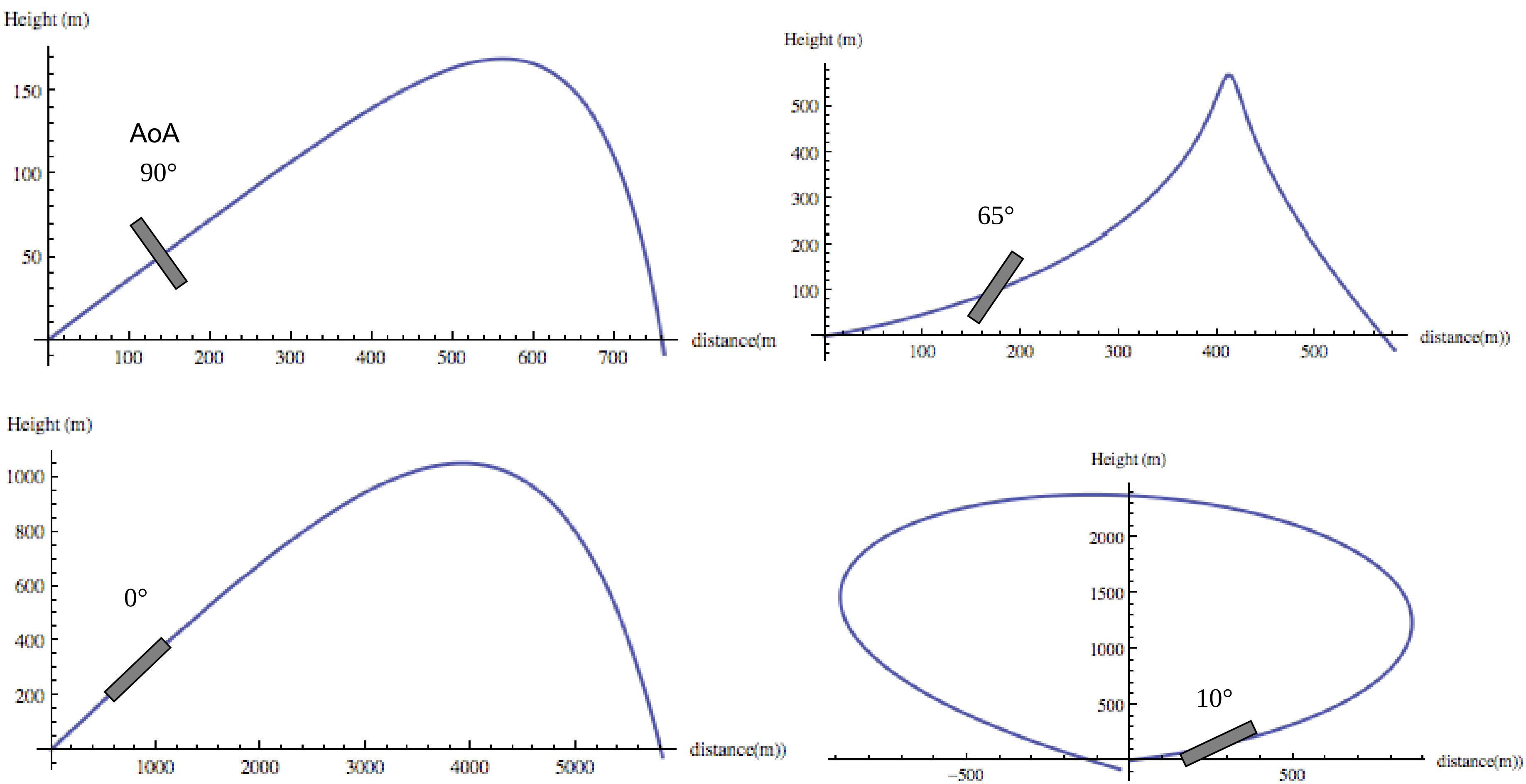
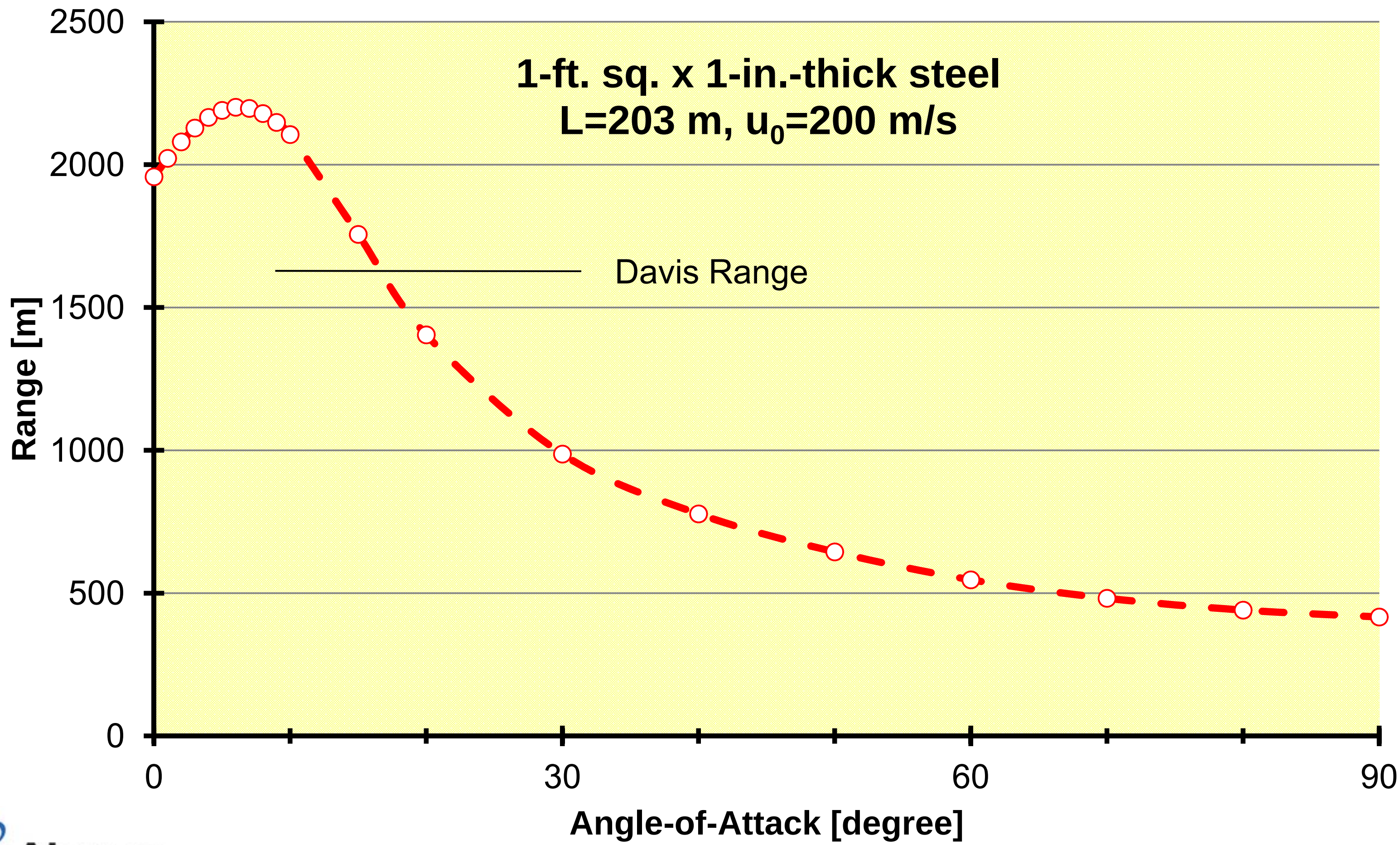


What lift can do for an aero-stable plate



Bottom Line:

- Identify furthest-flying primary fragment
  - Generally in contact with explosive
  - Greatest “thickness-density product”
    - Defines characteristic length, L
    - Apply Davis’ Rule
- Identify potential secondary fragments
  - Generally spaced from explosive
  - Eliminate or mitigate
    - Design to break up into pieces with small L
    - Knock’em down (mitigate)
  - Calculate initial velocity and potential range
    - This is a last resort

We've talked about models and approximations:

- Remember what George Box said:

"All models are wrong, but some are useful."

George E. P. Box, FRS